LA-UR--83-2895

DE84 001867

CONF-8308136--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: NUMERICAL SIMULATIONS OF CONVECTIVELY EXCITED GRAVITY WAVES

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SUBMITTED TO: Solar Seismology from Space Conf., Snowmass, CO, August 17-19, 1983

Los Alamos

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FORM NO 836 R4
ST NO 2629 5/81

NUMERICAL SIMULATIONS OF CONVECTIVELY EXCITED GRAVITY WAVES

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Magneto-convection and gravity waves are numerically simulated with a nonlinear, three-dimensional, time-dependent model of a stratified, rotating, spherical fluid shell heated from below. A Solar-like reference state is specified while global velocity, magnetic field, and thermodynamic perturbations are computed from the anelastic magnetohydrodynamic equations. Convective overshooting from the upper (superadiabatic) part of the shell excites gravity waves in the lower (subadiabatic) part. Due to differential rotation and Coriolis forces, convective cell patterns propagate eastward with a latitudinally dependent phase velocity. The structure of the excited wave motions in the stable region is more time-dependent than that of the convective motions above. The magnetic field tends to be concentrated over giant-cell downdrafts in the convective zone but is affected very little by the wave motion in the stable region.

1. INTRODUCTION

I would like to illustrate with numerical simulation how complex the global velocity and magnetic fields must be in the Sun, and how their structure and evolution in the stable region differ from that in the unstable, convective region. The dynamic dynamo model and the numerical method are described in Glatzmaier (1983). The anelastic MHD equations reduce to a 17th-order system of equations with each of the six dependent variables expanded in 1024 spherical harmonics and 17 Chebyshev polynomials. A semi-implicit time-integration scheme is employed. The anelastic approximation filters out acoustic waves but not gravity or convective modes.

A typical snapshot of the simulated motions is shown in Figure 1 where the mass flux (velocity times density) is plotted in the equatorial plane. The top and bottom boundaries correspond to 93% and 56% of the Solar radius, respectively. There are seven pressure scale-heights across the shell. The $(\nabla - \nabla_{AD})$ profile in Figure 2 defines the superadiabatic and subadiabatic regions. (The stable region in a standard Solar mixinglength model is much more subadiabatic than it is in this model. See further comments below.) Notice in Figure 1 how convective motions overshoot a short way into the stable (subadiabatic) region. This overshooting excites small amplitude gravity waves in the differentially rotating fluid.

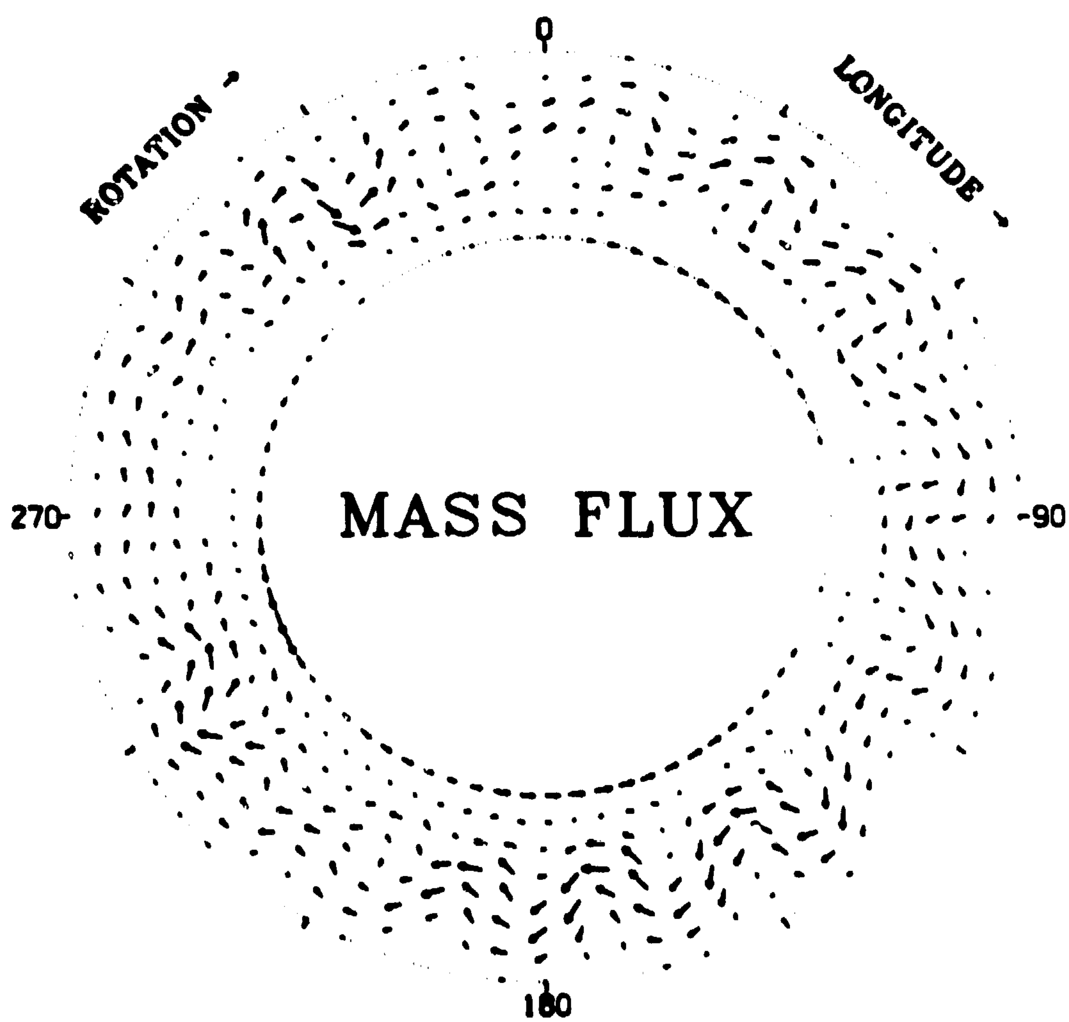


Figure 1. Mass flux vectors plotted in the equatorial plane viewed toward the north.

Generally, buoyancy forces do positive work in the superadiabatic region by driving convection; while, in the subadiabatic region, they do negative work by damping gravity waves. This is illustrated in Figure 2 where the horizontally averaged work done by buoyancy is plotted vs. radius. The negative buoyancy work in the stable region is small because the perturbations are small relative to those in the convection zone. Notice how buoyancy does positive work a short way into the subadiabatic region. This is due to the overshooting of sinking fluid that remains heavier than the surroundings for a short distance into the subadiabatic region. The negative work done by buoyancy near the top of the convection zone is required to help decelerate rising fluid and accelerate sinking fluid (Glatzmaier and Gilman 1981b).

We will examine the structure and evolution of the velocity and magnetic fields - first in the unstable (superadiabatic) region and then in the stable (subadiabatic) region.

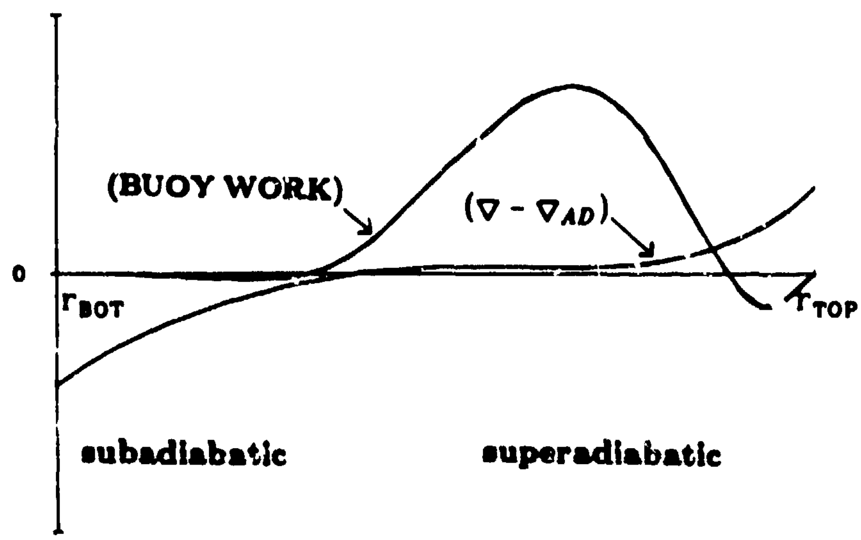


Figure 2. Horizontally averaged $(\nabla - \nabla_{AD})$ and buoyancy work density per time plotted vs. radius.

2. THE UNSTABLE REGION

In Figure 3, the radial component of the velocity is plotted (relative to the rotating frame of reference) in a spherical surface just below the top boundary at four different times. The snapshots were taken a week apart. As suggested by linear anelastic calculations (Glatzmaier and Gilman 1981b), north-south rolls are preferred because, for these, Coriolis forces are more easily balanced by pressure gradient forces. However, nonlinear, multimode calculations are required to study the complicated structure and evolution of the convective cells.

One can see, by examining these snapshots, how the cell pattern in the equatorial region propagates eastward relative to the patterns in the polar region. As a result, an updraft region is periodically sheared apart at mid-latitude and subsequently joined to the next updraft region. The eastward cell velocity in the equatorial region is about 10% of the average solar rotation rate.

There are two reasons for this type of evolution. The obvious one is the nonlinear effect of the latitudinal differential rotation. That is, the north-south rolls become deformed because the equatorial region rotates faster due to the transport of angular momentum (Gilman 1977, Glatzmaier and Gilman 1982). The other reason is a linear effect due to Coriolis forces (Glatzmaier and Gilman 1981a). As rising fluid in a north-south roll expands, Coriolis forces cause it to rotate in the opposite sense of the global rotation generating negative local vorticity. Positive local vorticity is generated when sinking fluid contracts. Consequently, since positive vorticity exists in north-south rolls that are east of updrafts and negative vorticity in rolls east of downdrafts, the phase of the north-south rolls propagates eastward. Since this effect is greatest where gravity is perpendicular to the rotation axis, the resulting eastward phase velocity is maximum in the equatorial region.

Now we examine, in Figure 4, the corresponding structure and evolution of the radial component of the magnetic field in the same spherical surface at the same four times. In this surface the magnetic energy density is approximately one thousand times smaller than the kinetic energy density. As a result, both magnetic field polarities tend to be concentrated over the downdrafts of the giant cells due to the convergence of horizontal flow (Glatzmaier 1983). This can be seen by carefully comparing Figures 3 and 4. Since the peak radial components of the magnetic field exist at mid-latitude, they do not experience the large eastward phase velocity of the convective cells in the equatorial region. However, by close examination, one can see how the magnetic field structure changes slightly as the convective rolls are sheared at mid-latitude.

3. THE STABLE REGION

The structure and evolution of the velocity and magnetic fields in the stable region are quite different than what has just been described for the unstable region. The radial component of the velocity is plotted in Figure 5 for the same four times but in a spherical surface just above the bottom boundary. Since here buoyancy is a restoring force, the velocity consists of oscillatory wave motions. However, these are not simple linear gravity modes but highly structured, time-dependent, nonlinear waves which are continually being excited by convective overshooting and affected by Coriolis and Lorentz forces on a differentially rotating fluid background in spherical geometry.

The corresponding radial component of the magnetic field, plotted in Figure 6, shows little change with time and very little correlation with the velocity field. This is probably because the oscillatory fluid motions deep in the stable region do not have horizontal convergence properties as do the convective motions in the unstable region. Also, the magnetic energy density at this depth is only ten times smaller than the kinetic energy density.

4. SUMMARY

These numerical simulations were presented to illustrate how complicated the structure and evolution of the velocity and magnetic fields must be in the Sun. They illustrate the latitudinally dependent eastward propagation and resulting shearing of the north-south rolls. Certainly this makes the observation of Solar giant cells difficult, especially when the data is averaged over several weeks in order to reduce the small-scale Solar noise (Howard and LaBonte 1980, Gilman and Glatzmaier 1980). On the other hand, the simulated large-scale magnetic fields, concentrated over giant-cell downdrafts near the surface at mid-latitude, change very little with time and resemble large-scale Solar magnetic field observations (Howard 1977).

The simulations also illustrate how complicated gravity wave motions are in the stable region and how they differ from convective motions in the unstable region. However, the simulations were not meant to predict periods of the excited gravity modes. The periods, which are of the order of a few weeks, probably are not realistic for two reasons. The model's impermeable bottom boundary forces an artificial node and enhances the higher order spherical harmonic modes (smaller scales). In addition, $(\nabla - \nabla_{ad})$ in the stable region is much smaller than it is in a standard Solar model; consequently, the gravity wave periods are much larger than they would be if the stable region were more subadiabatic.

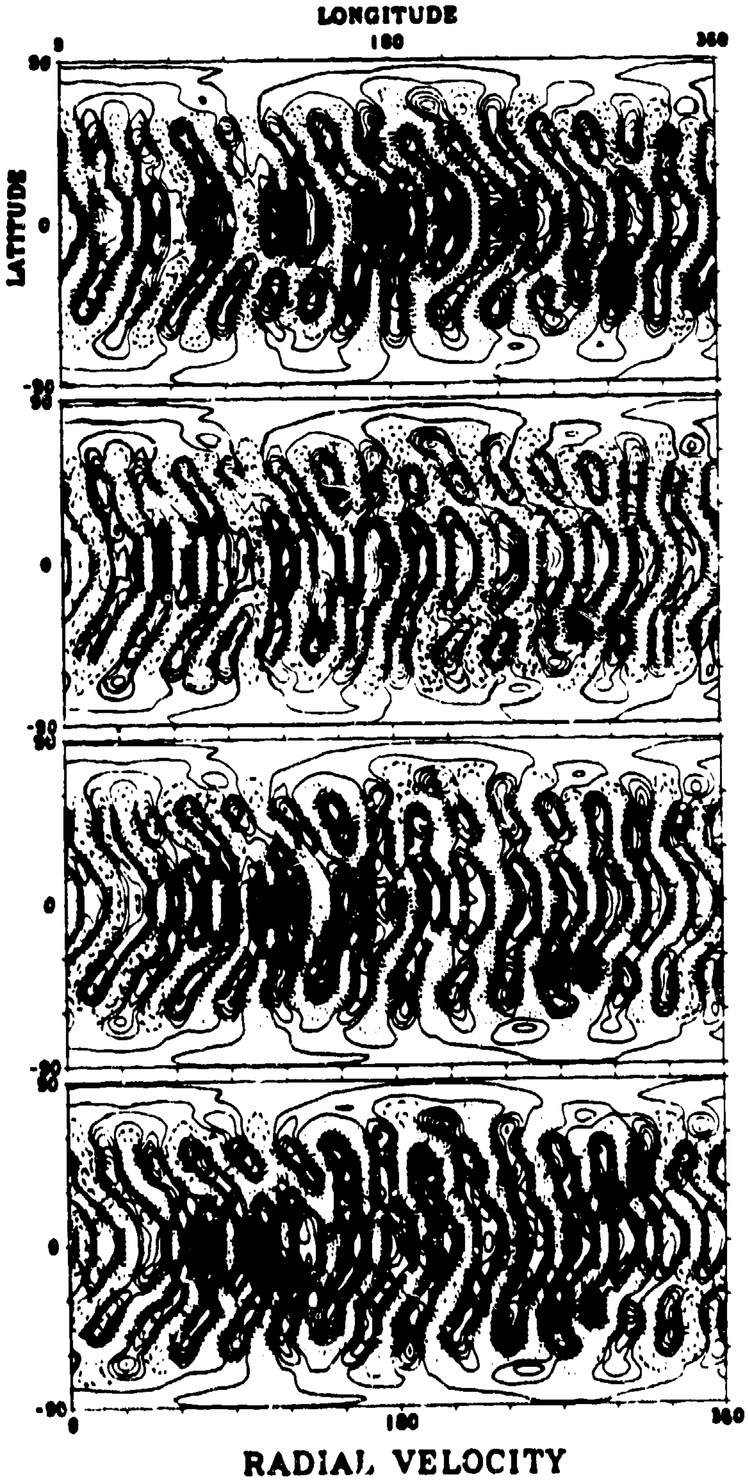
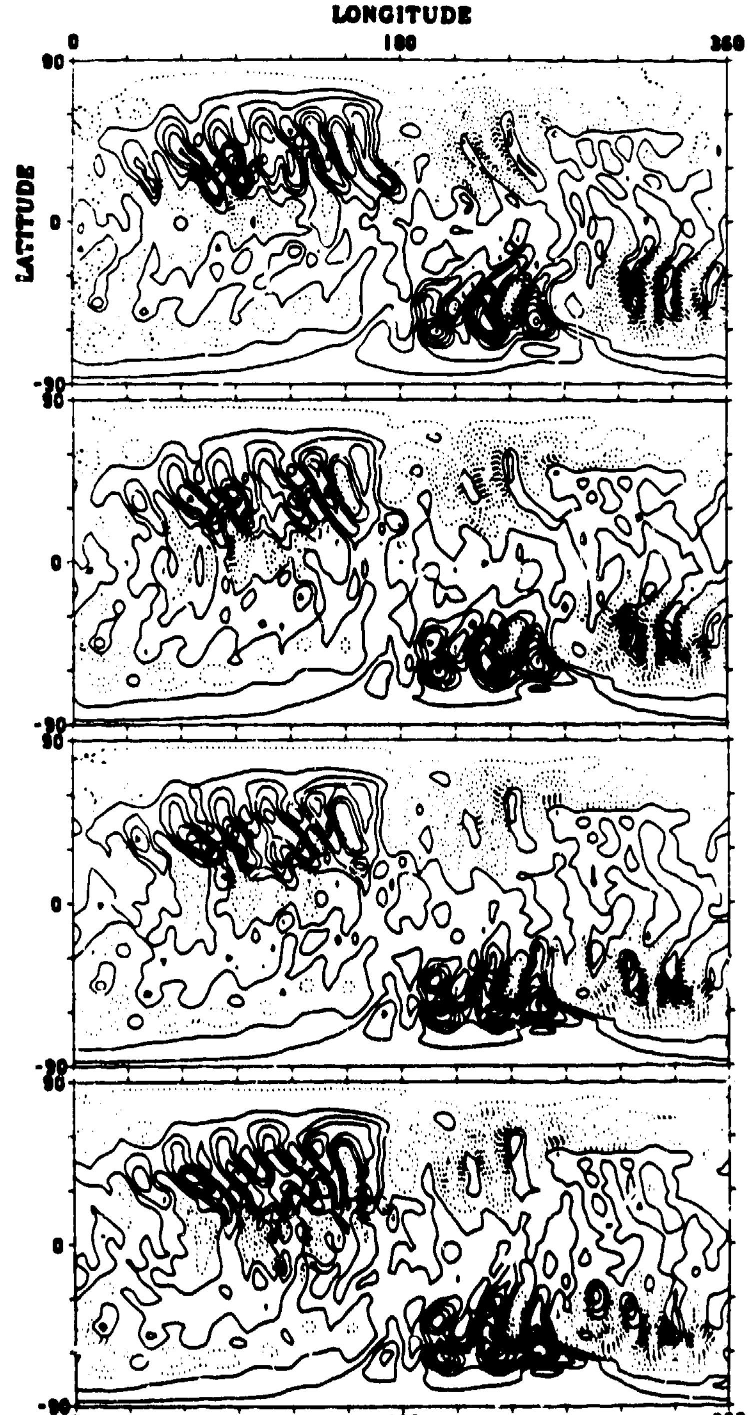


Figure 3. Radial components of velocity plotted in a spherical surface just below the top boundary at one week intervals. Solid (broken) contours represent upward (downward) velocity.



RADIAL MAGNETIC FIELD

Figure 4. As in Figure 3, but for the radial component of the magnetic field.

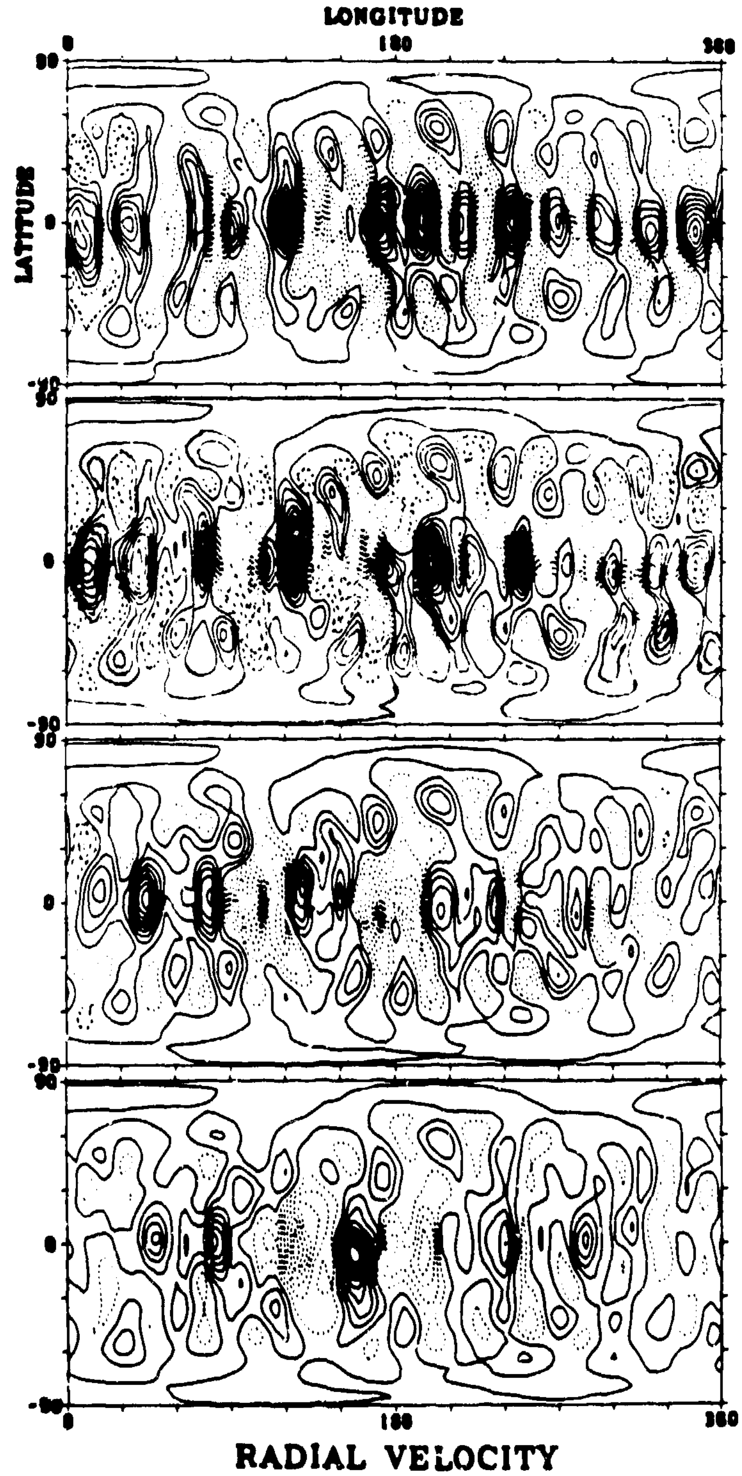


Figure 5. As in Figure 3, but for a spherical surface just above the bottom boundary.

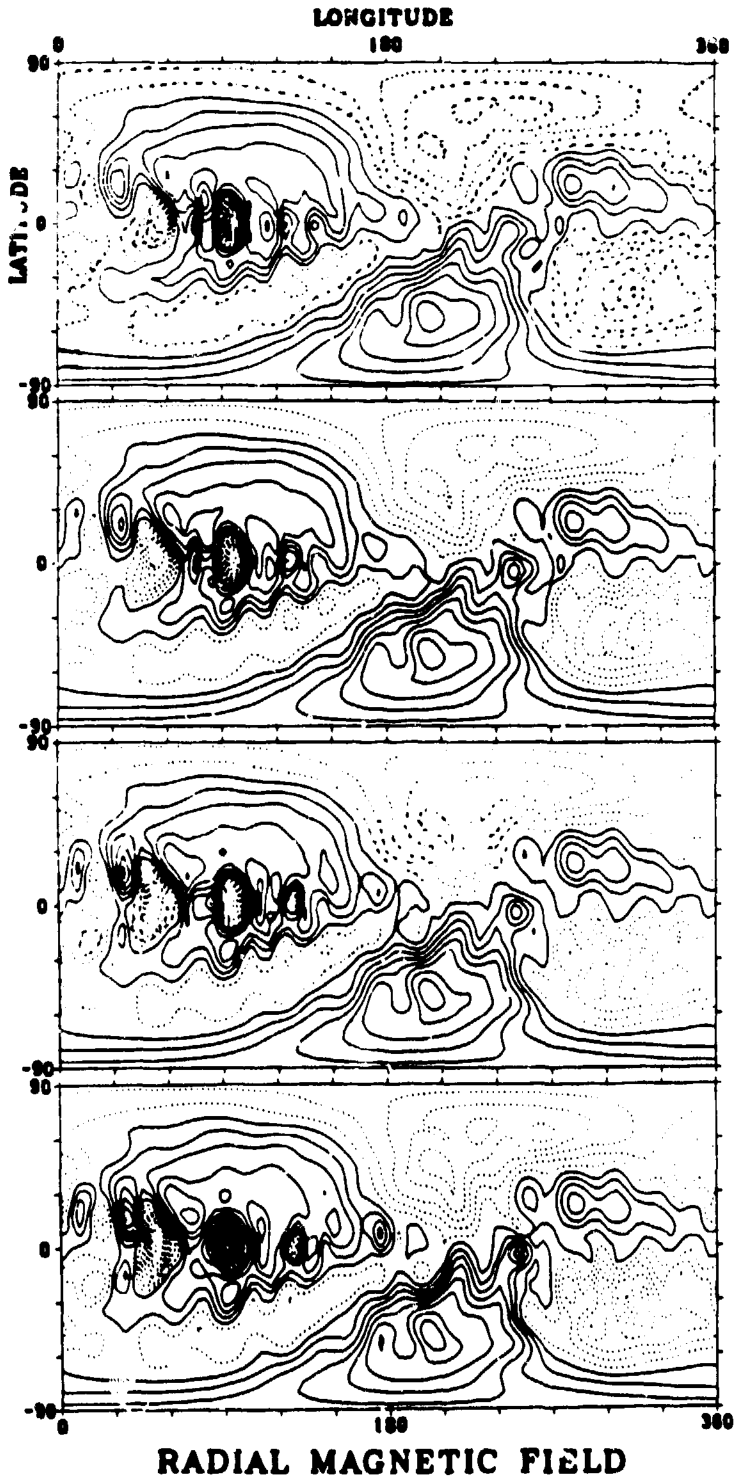


Figure 6. As in Figure 5, but for the radial component of the magnetic field.

A new version of the code is being developed that will model an entire sphere, employ time-dependent sub-grid scale eddy diffusivities, and incorporate a $(\nabla - \nabla_{ad})$ profile based on a standard Solar model. This new code should be able to predict more realistic gravity wave amplitudes and periods. However, the present results illustrate how difficult it would be to observe these highly structured, time-dependent gravity modes, especially if the interpretation is based on linear models that do not account for convective motions, Coriolis forces, Lorentz forces, or differential rotation.

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